



# Aeroservoelastic Modeling of Body Freedom Flutter for Control System Design

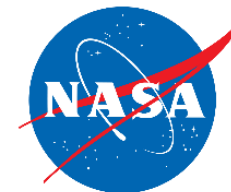
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JEFFREY OUELLETTE

*NASA ARMSTRONG FLIGHT RESEARCH CENTER*

AEROSPACE CONTROL AND GUIDANCE SYSTEMS COMMITTEE MEETING #119

MARCH 29-31, 2017



# Increasing Aspect Ratio

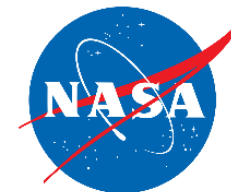
Improves aerodynamic performance

Increased flexibility

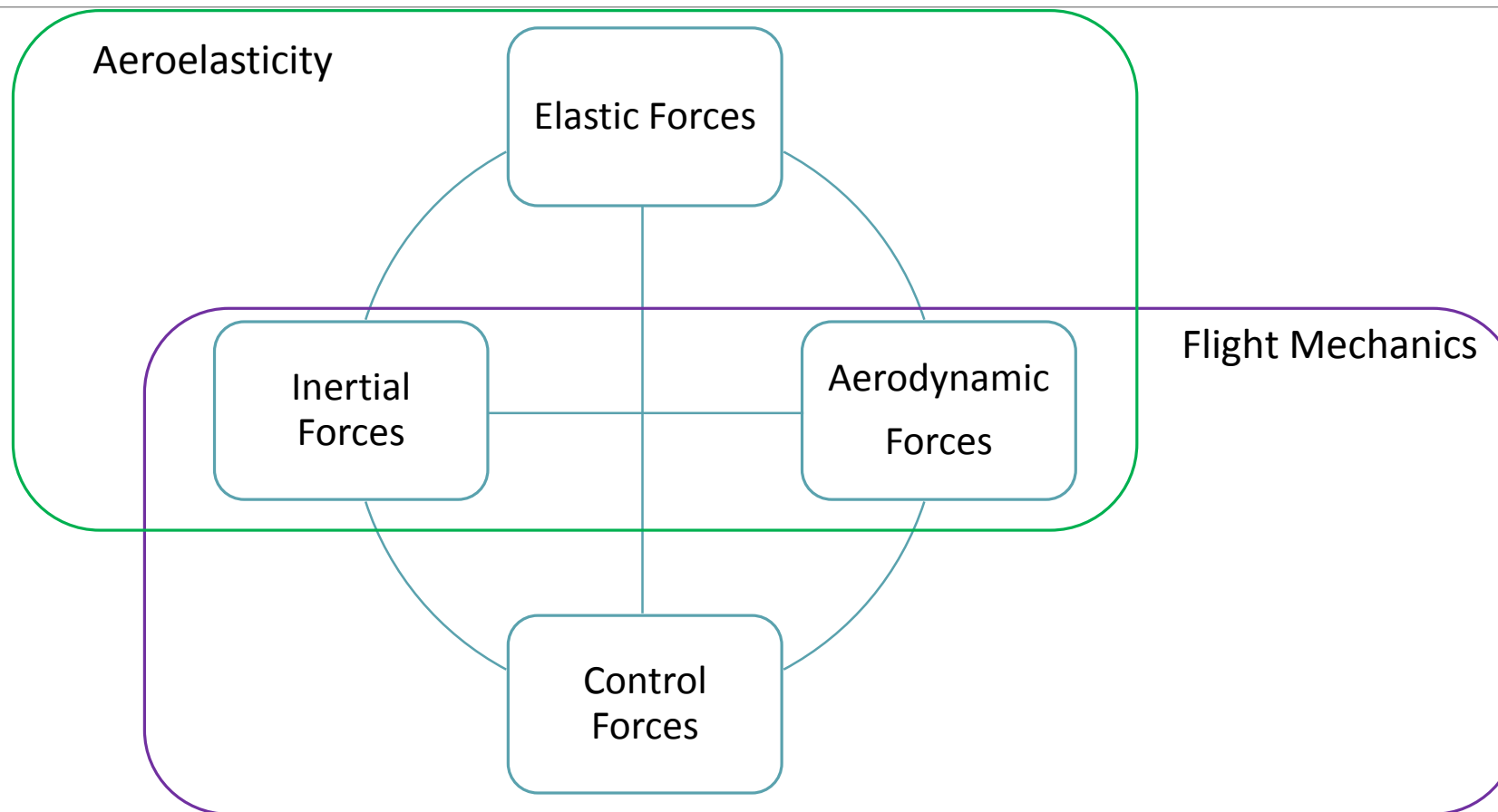
- Reduces aeroelastic margin
- Significant weight penalty to maintain margin

Greater interaction with the flight dynamics

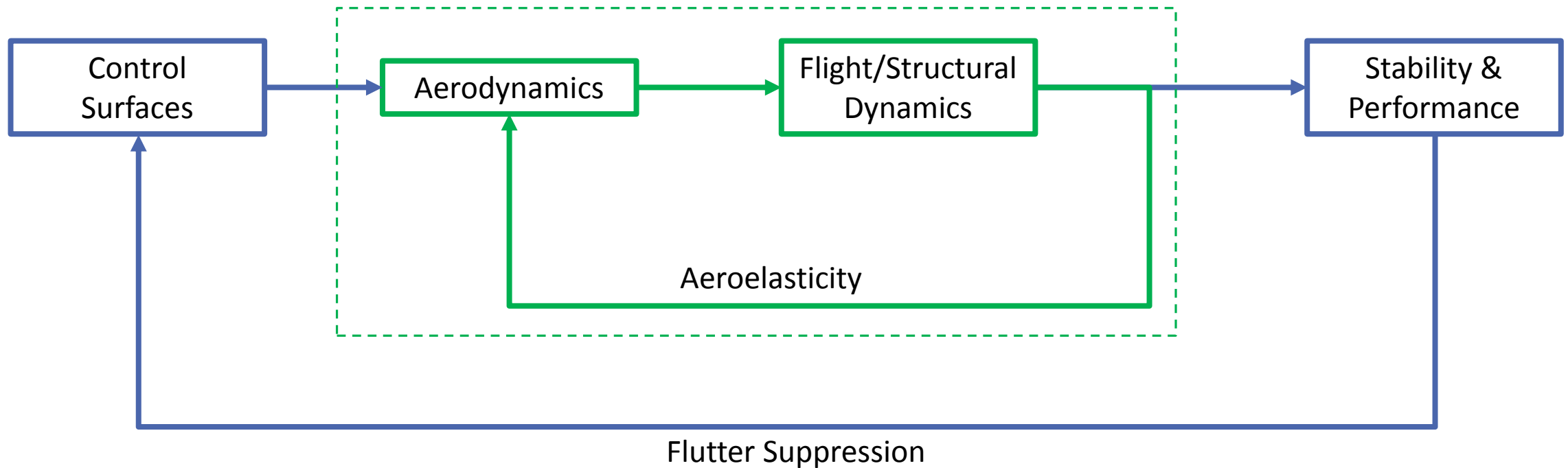


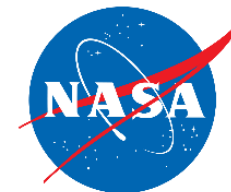


# Aeroservoelasticity



# Aeroelasticity as a closed loop





# Active Flutter Suppression

Use flight controls to maintain stability

- Does not have a weight penalty

Past efforts have had mixed results

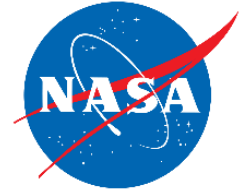
- B-52 successfully suppressed flutter 1973
- DAST was unsuccessful, circa 1980
- See AIAA 2017-1119, by Eli Livne

Body freedom flutter

- Structural dynamics destabilize flight dynamics



# Multi-Utility Technology Testbed X-56A MUTT



Designed for testing active flutter suppression

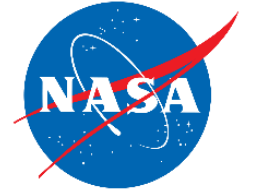
- Flexible wings have unstable flutter modes
- AFRL Funded
- Lockheed Martin Build

For developing technologies



# Modeling Philosophy

## How does MUTT translate to N+3?



### Definition of model interfaces

- Discipline models will change
  - Origin of the parameters
  - Form of the equations
- The interfaces change less
  - Inputs and outputs are very common

### Physics Based Modeling

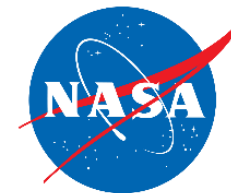
- Predictive capability of the models
- How do the physics define the interface
- How do we model before flight test

### Verifiable

- Keep complexity in check







# Then and Now

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Found several issues with existing modeling approaches

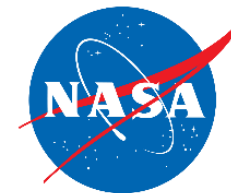
## Development to date

- Keep trying to patch issues
- Inconsistencies between disciplines
  - Coordinate systems
  - Definition of parameters
  - Etc.

## Building upon previous approaches

- Intentionally similar to existing approaches
- Addressing inconsistencies between disciplines





# Structural (Modal) States

Deformed shape is combination of mode shapes

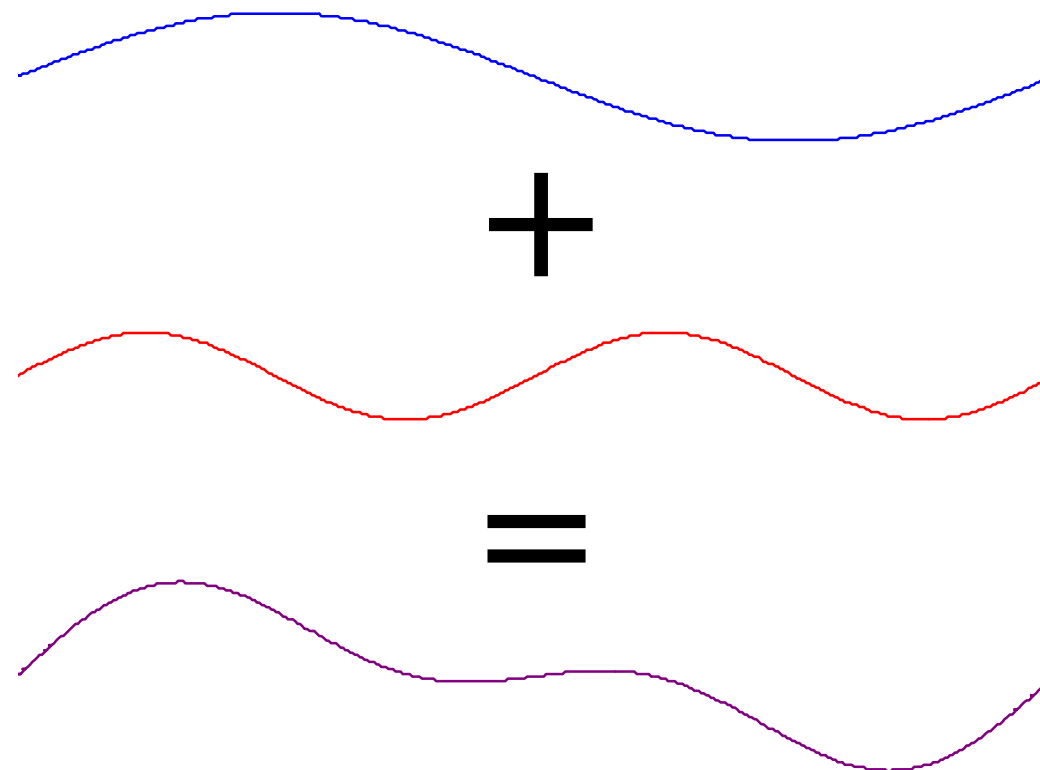
- What shapes do we use?

## Orthonormal Modes

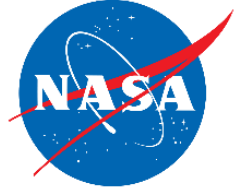
- Standard in structural analysis
- Modes do not exchange energy
  - No inertial coupling
  - No elastic coupling
- Aerodynamics add

## Mean Axis

- Used for integration of nonlinear flight dynamics
- No inertial coupling between rigid body and flexible modes
  - Orthonormal modes are sufficient, but not necessary



# The Problem: State Consistency



Models generally made for specific mass/flight condition

Full envelope design

- What happens between these conditions?

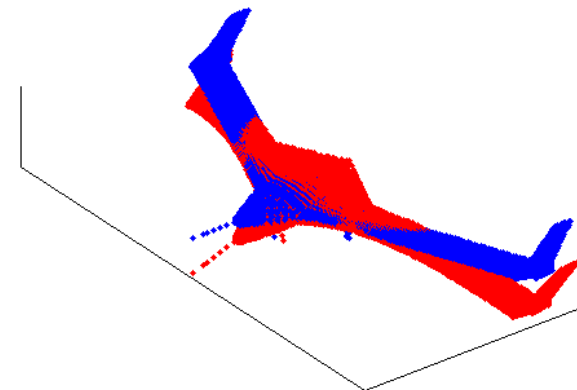
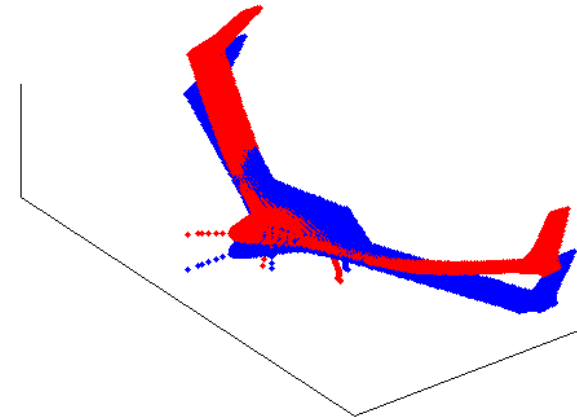
No sign convention in mode shapes

- The direction of the mode shapes can change

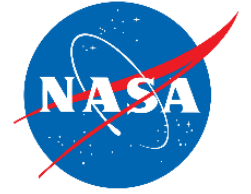
New modes can appear with masses

Ordering of the modes can change

- Finite element models sort by frequency



# Previous methods: State Consistency



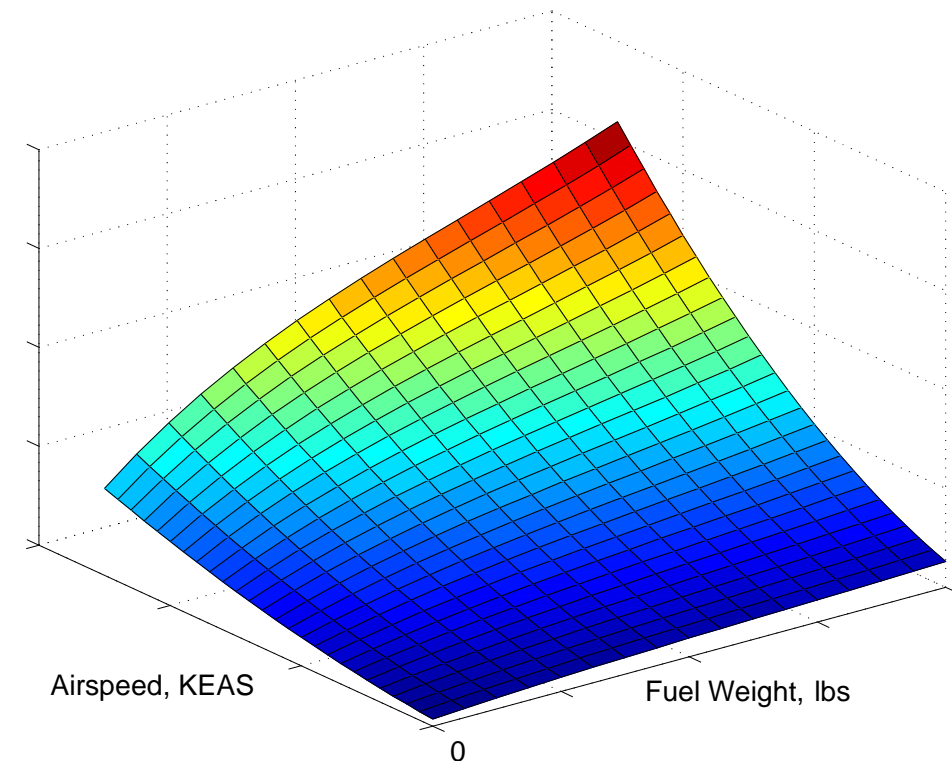
Often simply ignored

- Does not appear on simpler configurations
- Can be bypassed by specific control architectures

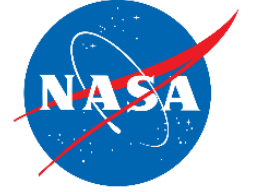
Corrective transformations

- Applied to final models
- Often not robust
- Are there equivalent states?

## Consistent Coefficient



# The Solution: Assumed Modes



## Using an assumed mode method

- The same mode shapes are used for all conditions
- Changes are in modal mass and stiffness matrices
  - To match kinetic and potential (strain) energy
- Aerodynamic coefficients are constant

## Assumed modes method is quite old

- Using for state consistency is new

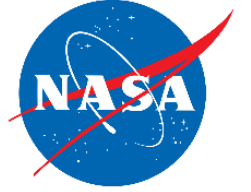
## Which mode shapes to use?

- Are there sufficient mode shapes?
- Are all of the modes represented?

This is an issue with any method

# Assumed Modes: Other Benefits

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## Uncertainty

- There is no uncertainty in the mode shape
- Uncertainty is captured in other physical parameters

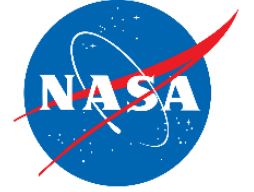
## Structural Nonlinearities

- Can generate parameter varying model
- Only mass and stiffness matrices change

## Constant Aerodynamic Coefficients

- Structural properties don't effect the behavior of the airflow
- Aerodynamic coefficients do not change with structural properties

# The Problem: Low frequency Dynamics



## Why do we care?

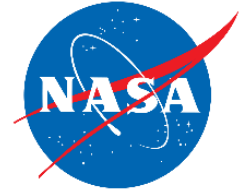
- Static Instabilities
  - Short-period frequency is reduced
  - Very strong coupling with the phugoid
- Often less control margin
  - MIL-STD-9490 below 0.06 Hz
  - Requires 4.5 dB gain margin
  - Requires 30 deg phase margin

Do not want separate models for these dynamics

## What are the primary effects?

- Phugoid mode
  - Dominates low frequency behavior
  - Transfer of energy
    - Kinetic energy
    - Potential energy (gravity)
- Large velocity variations
  - Flutter methods assume constant velocity

# Previous method: Apply rigid body model



## Velocity Variations

- Forces change due to changes in dynamic pressure
  - $\frac{\partial}{\partial v} \bar{q} = 2 \frac{\bar{q}}{v}$
- Applying 6DoF coefficients neglects change in force on the structure

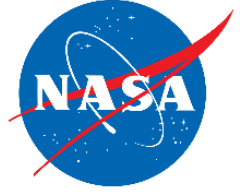
- $A_{1aug} = S \begin{bmatrix} -2C_{D_0} & 0 & C_{L_0} & 0 & \dots & 0 \\ -2C_{L_0} & 0 & -C_{D_0} & 0 & \dots & 0 \\ 2\bar{c}C_{D_0} & 0 & 0 & 0 & \dots & 0 \\ 2C_{\eta 1_0} & 0 & 0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 2C_{\eta 1_0} & 0 & 0 & 0 & \dots & 0 \end{bmatrix}$

## Gravity

- Can use 6 DoF results
  - If origin is at the center of gravity
- Assumed modes complicates this
  - Mass matrix is not diagonal
  - Center of gravity moves with structural deformations



# The Solution: Gravitational Forces

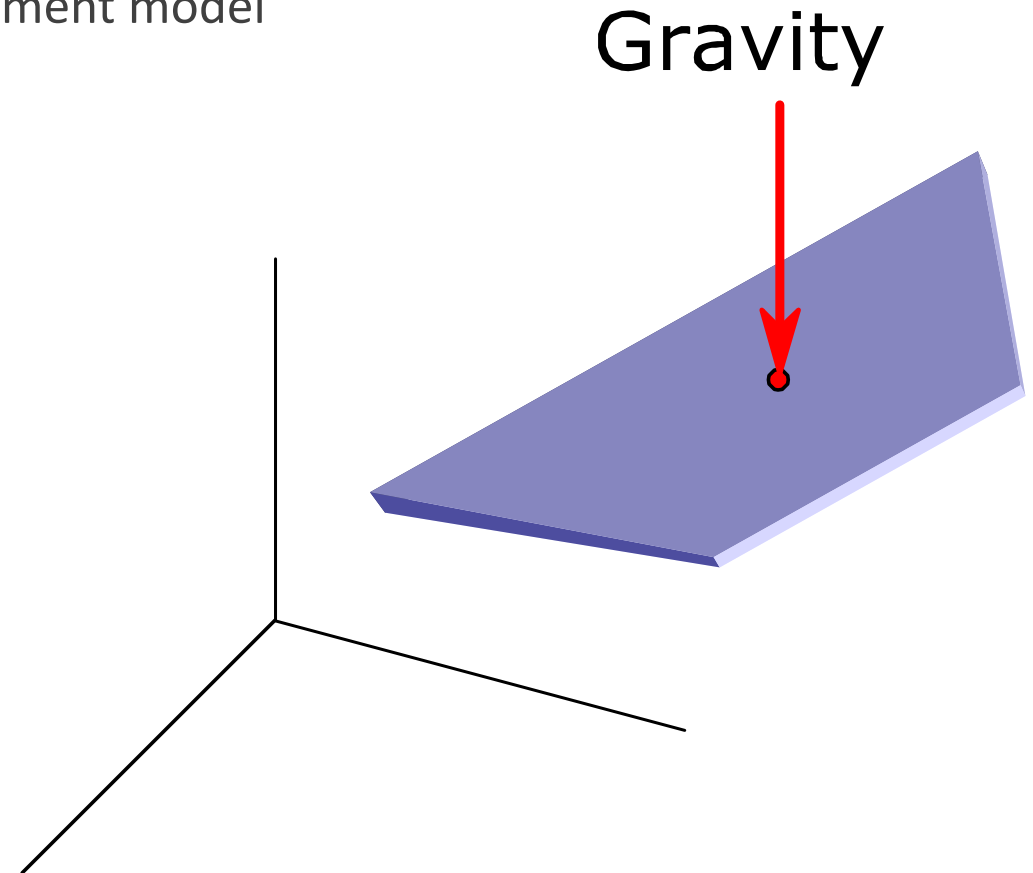


Using the complete mass matrix from the finite element model

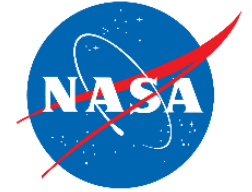
- Modal mass is not diagonal
  - Due to assumed modes method

For each element

- $\mathbf{F}_{gravity} = m_{element} g(\hat{\mathbf{z}} + \mathbf{T}(\alpha_0)\boldsymbol{\theta}_{element})$ 
  - $\hat{\mathbf{z}}$ : Vertical vector
  - $\mathbf{T}(\alpha_0)$ : Rotation matrix from trim angle
  - $\boldsymbol{\theta}_{element}$ : Rotation of element from mode shape



# The Problem: Unsteady Aerodynamics



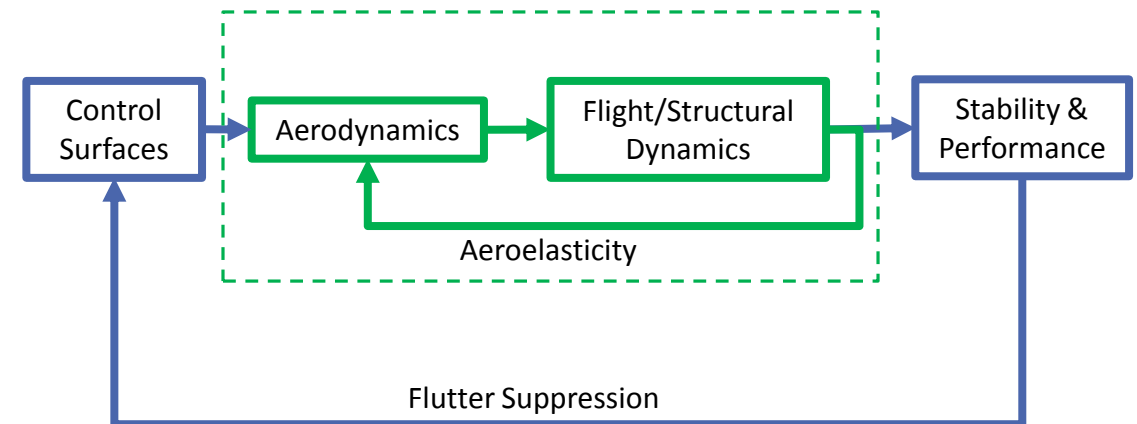
## Flight dynamics

- Low frequency
- Aerodynamics are algebraic
  - Depend only on the current state

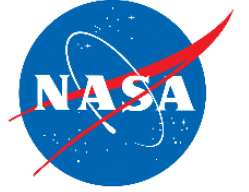
## Structural Dynamics

- High frequency
  - On the order of the dynamics of the flow
- Significant delays in the response

Need to model the flow dynamics



# The Problem: Unsteady Aerodynamics

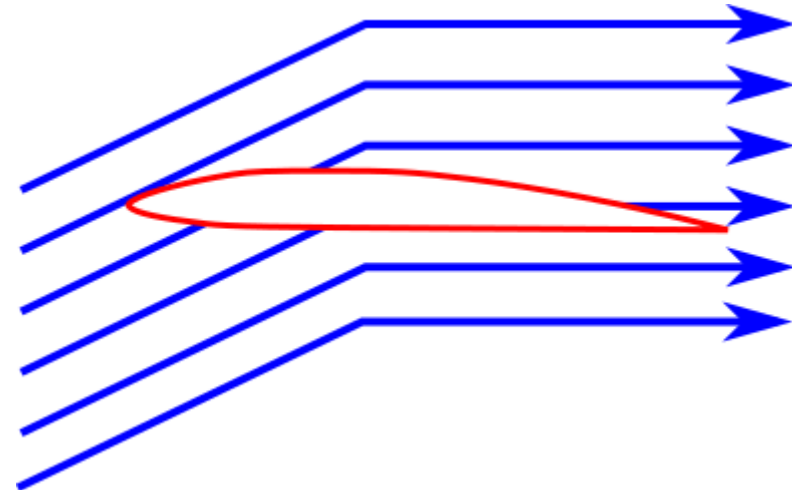


## Time scales

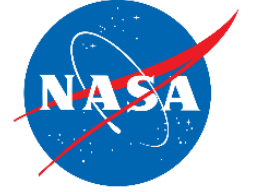
- Wide range required
  - Very long for phugoid
  - Very short for structural dynamics
- Increases computational cost

## Frequency domain aeroelasticity tools

- Considering harmonic motions simplifies the dynamics
- No closed form solution from frequency response to time history
- Time histories are required for evaluating closed loop performance



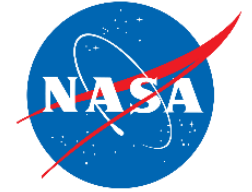
# Previous method: Rational Function Approximation



## Rogers Rational Function Approximation

- $\{\mathbf{q}\} \approx (\mathbf{A}_0 + \mathbf{A}_1 ik + \mathbf{A}_2 k^2 + \mathbf{D}(ik\mathbf{I} - \mathbf{R})^{-1}\mathbf{E}ik)\boldsymbol{\eta}$
- Has been used many times (40+ years old)
- Developed with weak interactions between flight dynamics and aeroelasticity
- Uses a modal coordinate system
  - Inertial coordinate system (origin is fixed in space)
  - Does not work for flight mechanics
    - Origin must move with the aircraft

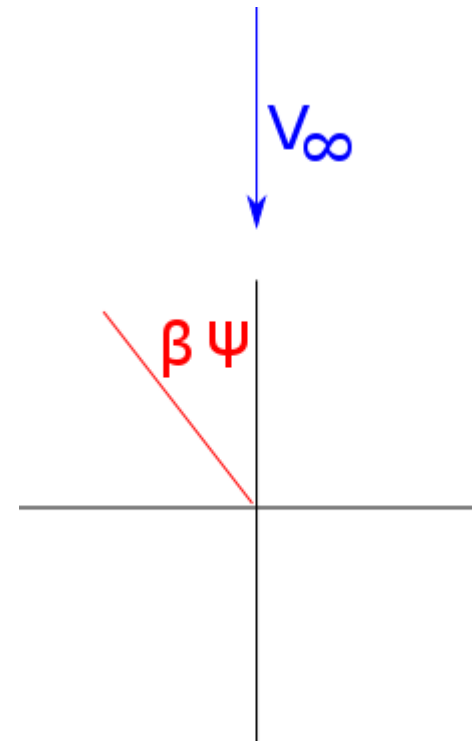
# Previous method: Time domain transformation



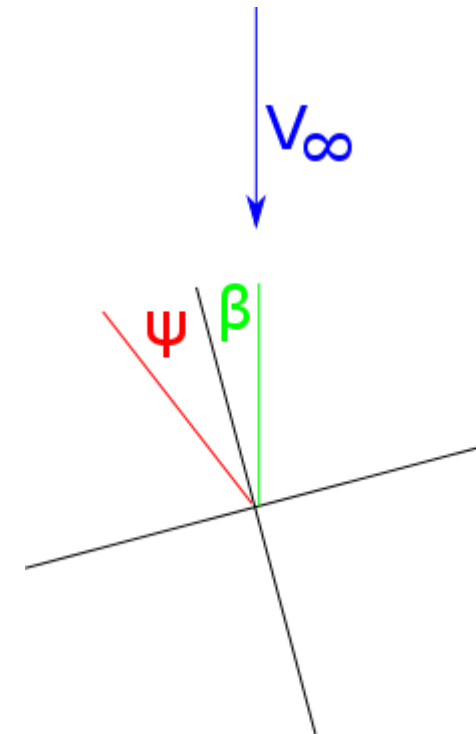
## Transformation

- Applied to final model
- Equivalent to
  - $A_0^* = A_0 T_{\eta 2x} + A_1 T_{\dot{\eta} 2x}$
  - $A_1^* = A_1 T_{\dot{\eta} 2u} + A_2 T_{\eta 2x} T_{\eta 2x}^{-1} T_{\dot{\eta} 2u}$
  - $A_2^* = A_2 T_{\dot{\eta} 2u}$
- Results in erroneous coefficients
  - Vehicle heading does not effect aerodynamic forces
  - Issues are emphasized in model reduction
  - Removing increases the error in the RFA

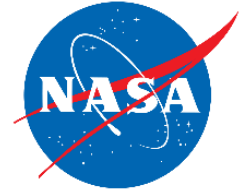
Steady Modal Axis



Steady Stability Axis



# The Solution: Frequency domain Transformation



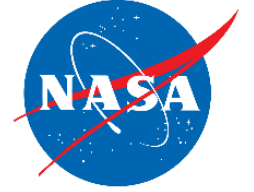
Apply transformation directly to frequency domain aerodynamics

$$\circ \begin{Bmatrix} ik\boldsymbol{\eta} \\ \boldsymbol{\eta} \end{Bmatrix} = \begin{bmatrix} \mathbf{T}_{\dot{\eta}2u} & \mathbf{T}_{\dot{\eta}2x} \\ 0 & \mathbf{T}_{\eta 2x} \end{bmatrix} \begin{Bmatrix} \mathbf{u} \\ \mathbf{x} \end{Bmatrix}$$

Stability Axis RFA

- $\{\mathbf{q}\} \approx \mathbf{A}_0\mathbf{x} + (\mathbf{A}_1 + \mathbf{A}_2 ik + \mathbf{D}(ik\mathbf{I} - \mathbf{R})^{-1}\mathbf{E})\mathbf{u}$
- Separate positions ( $\mathbf{x}$ ) and velocities ( $\mathbf{u}$ )
- Euler angles appear only in  $\mathbf{A}_0$ 
  - Only need to constrain single matrix
  - Curve fit remains minimum error solution

# Stability Axis RFA: Other Benefits



## Model Calibration/Tuning

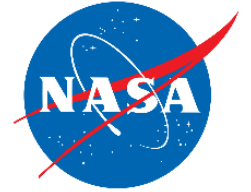
- Quasi-Steady Model
  - $A_0x + (A_1 - DR^{-1}E)u$
- Form identical to classical flight mechanics

## Integration with lookup tables

- Set quasi-steady to zero
  - $A_1 = DR^{-1}E$
- Allows non-linear aero tables
  - Unsteady model is increment to tables
  - Does not double count loads
  - Captures unsteadiness
  - Captures rigid-flexible coupling



# Applying the method: X-56A MUTT



Designed for testing active flutter suppression

- Flexible wings have unstable flutter modes

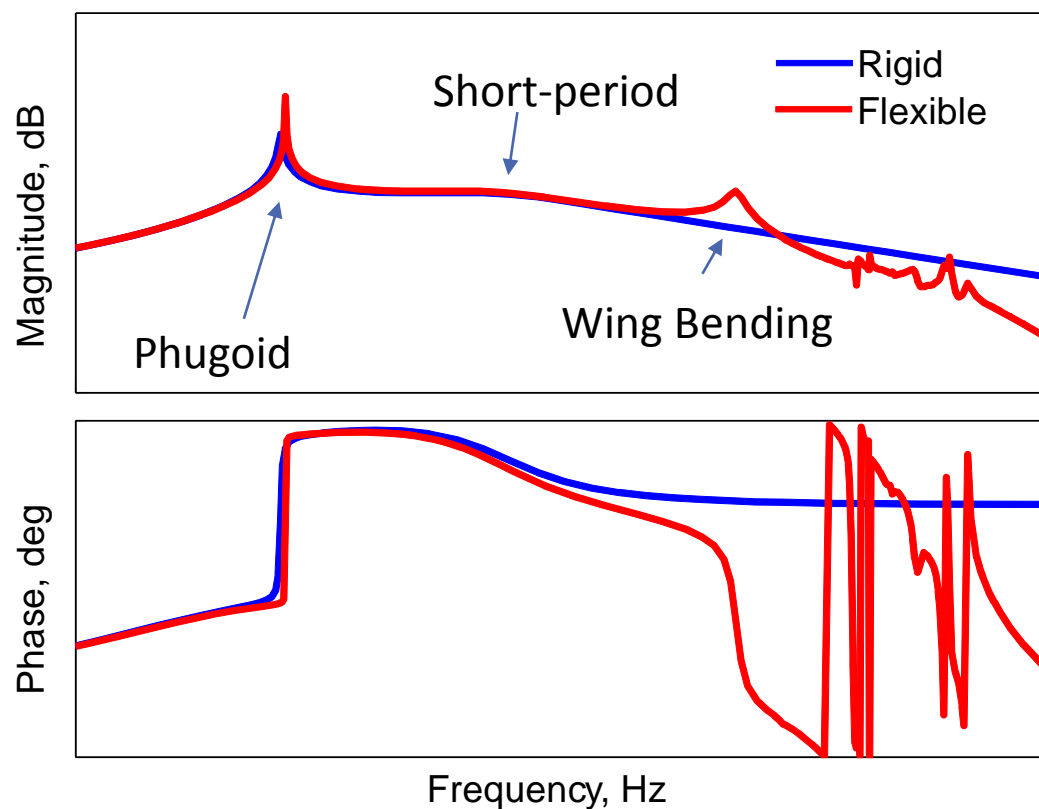
Currently have stiff wing data

- No unstable flutter modes

Using frequency domain potential flow aerodynamics



# Results



## Comparing to rigid models

- Basic 6-DoF model

## Matching the flight dynamics

- Short-period
- Phugoid

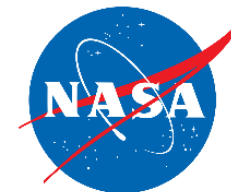
## Does not capture structural modes

## Higher roll-off and phase loss

- Sensors
- Unsteady aero

## Structural control

- Requires higher bandwidth controller



# Flight Data

## INPUTS

Orthogonal Multisines

High Bandwidth

Reduced Surface Rates

Short Maneuvers

Statistical Reputability

## TEST POINTS

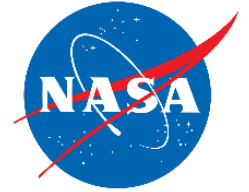
Test Case	Fuel Mass	Airspeed	Input
<b>1</b>	<b>Low</b>	<b>Low</b>	<b>Pitch</b>
2	High	Low	Pitch
<b>3</b>	<b>Low</b>	<b>High</b>	<b>Pitch</b>
<b>4</b>	<b>Low</b>	<b>High</b>	<b>Roll</b>

Low fuel emphasize assumed modes

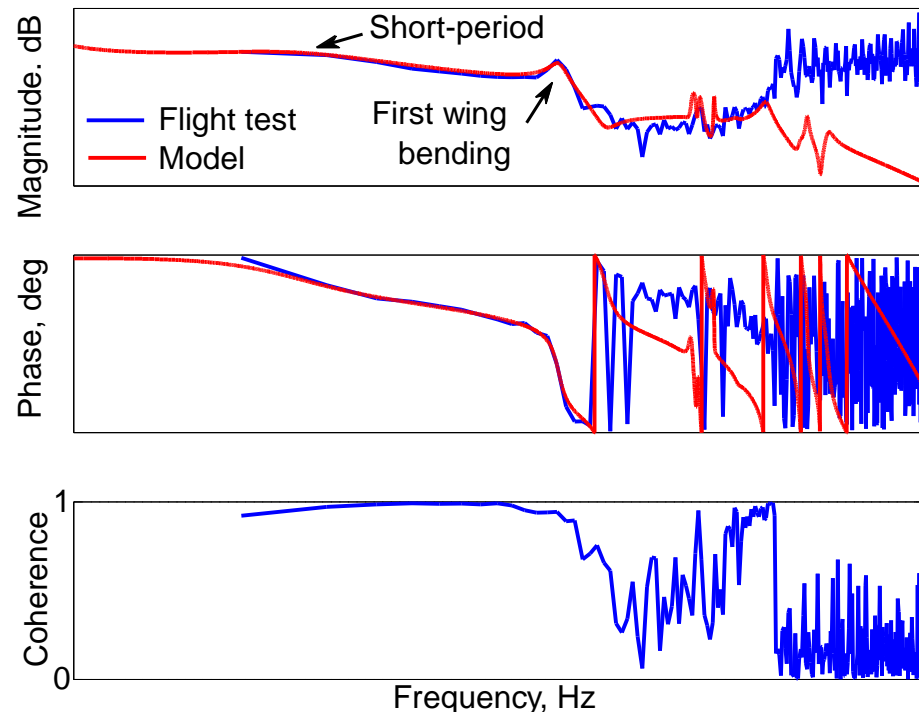
Low speed emphasizes aerodynamic lags

High speed emphasize aerodynamic coupling

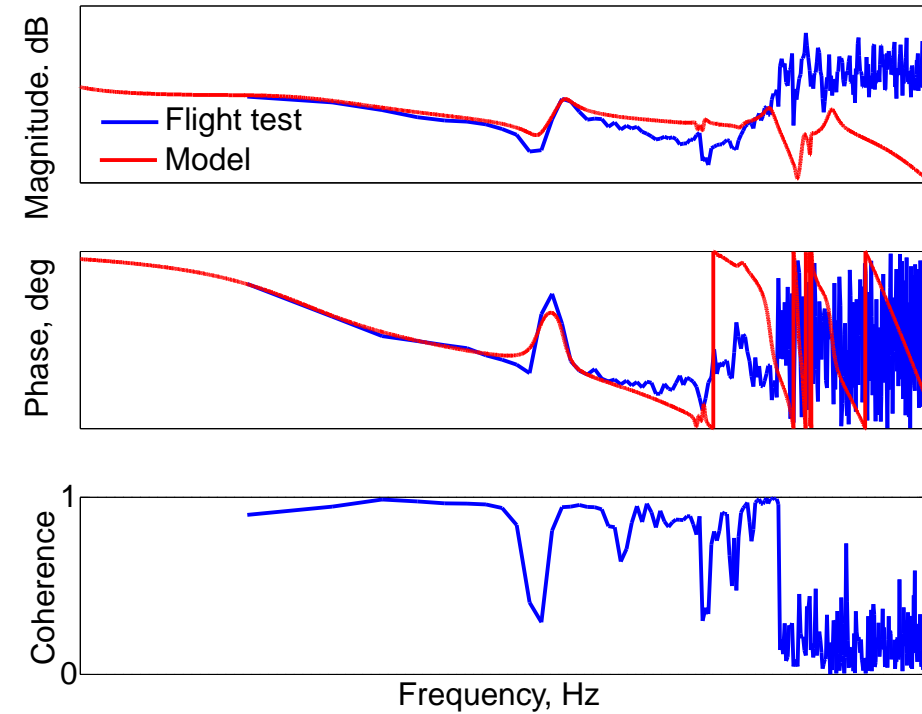
# Flight Data Comparison: Pitch response, low fuel, low speed



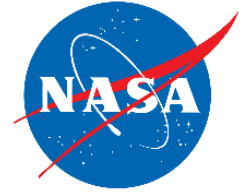
## PITCH RATE



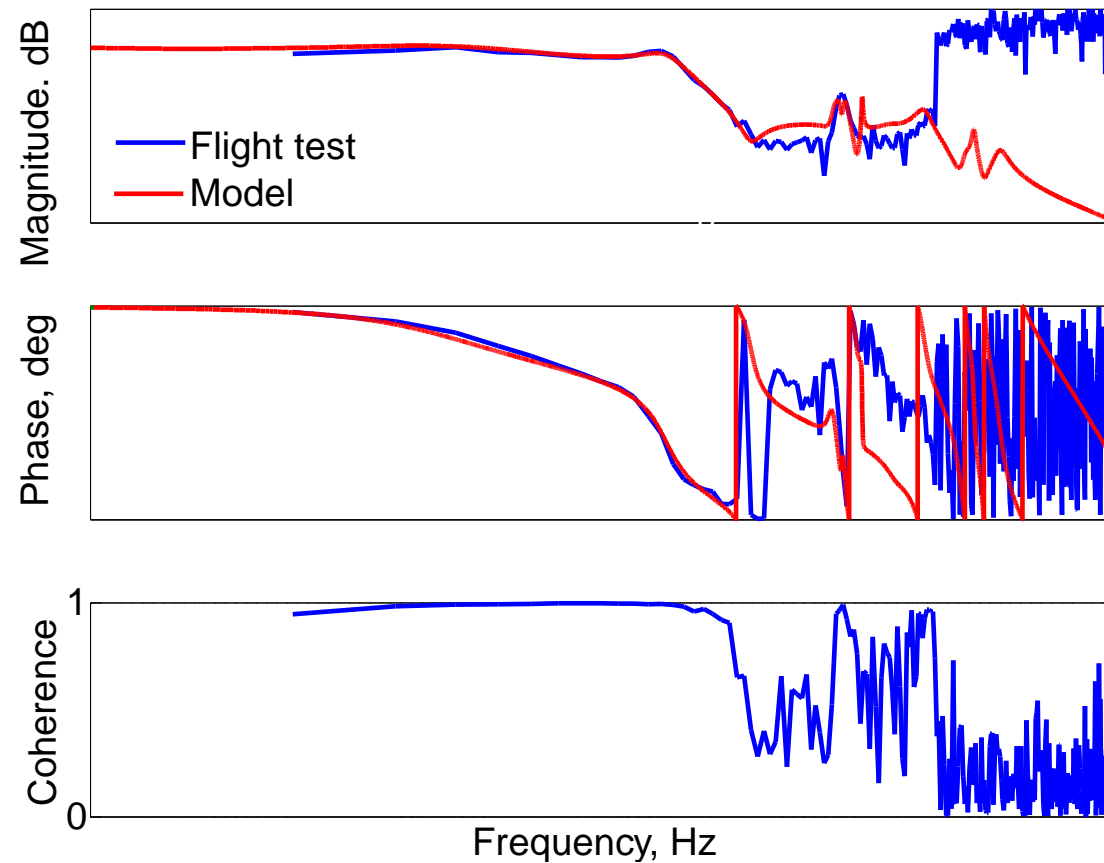
## WING TIP ACCELEROMETER



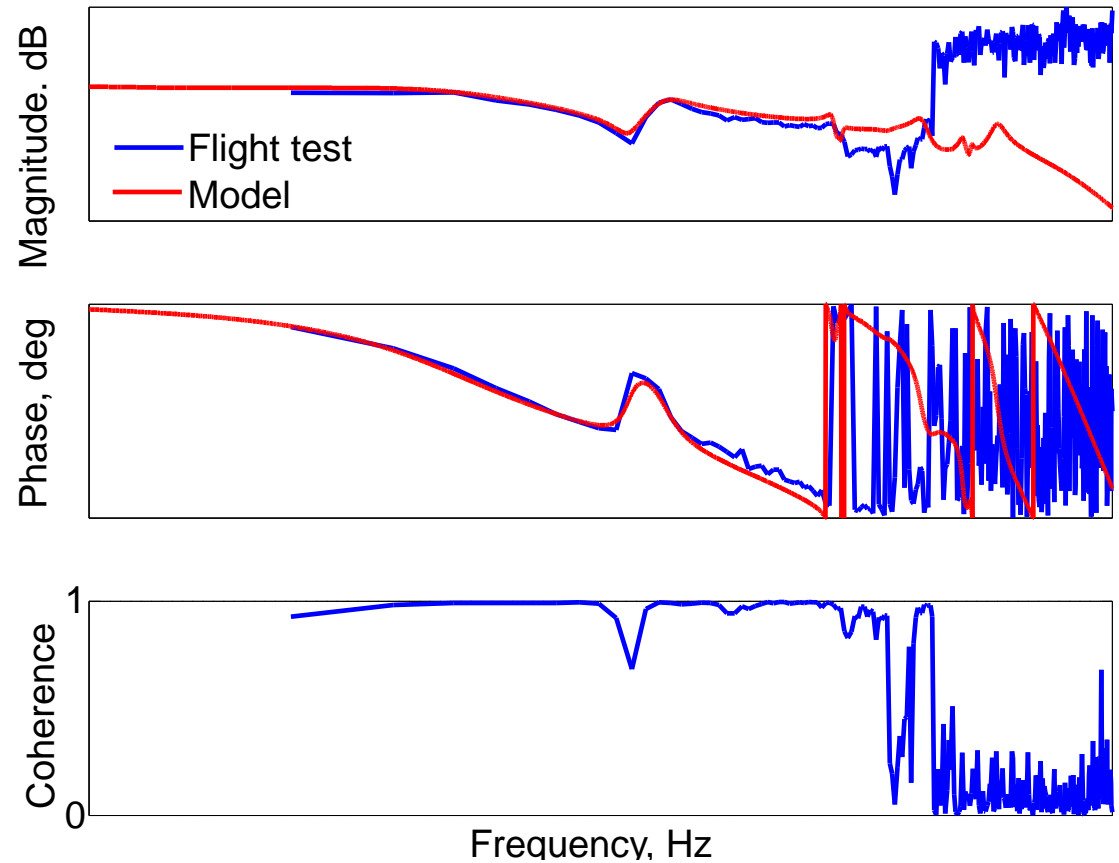
# Flight Data Comparison: Pitch response, low fuel, high speed



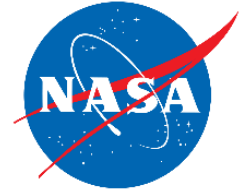
## PITCH RATE



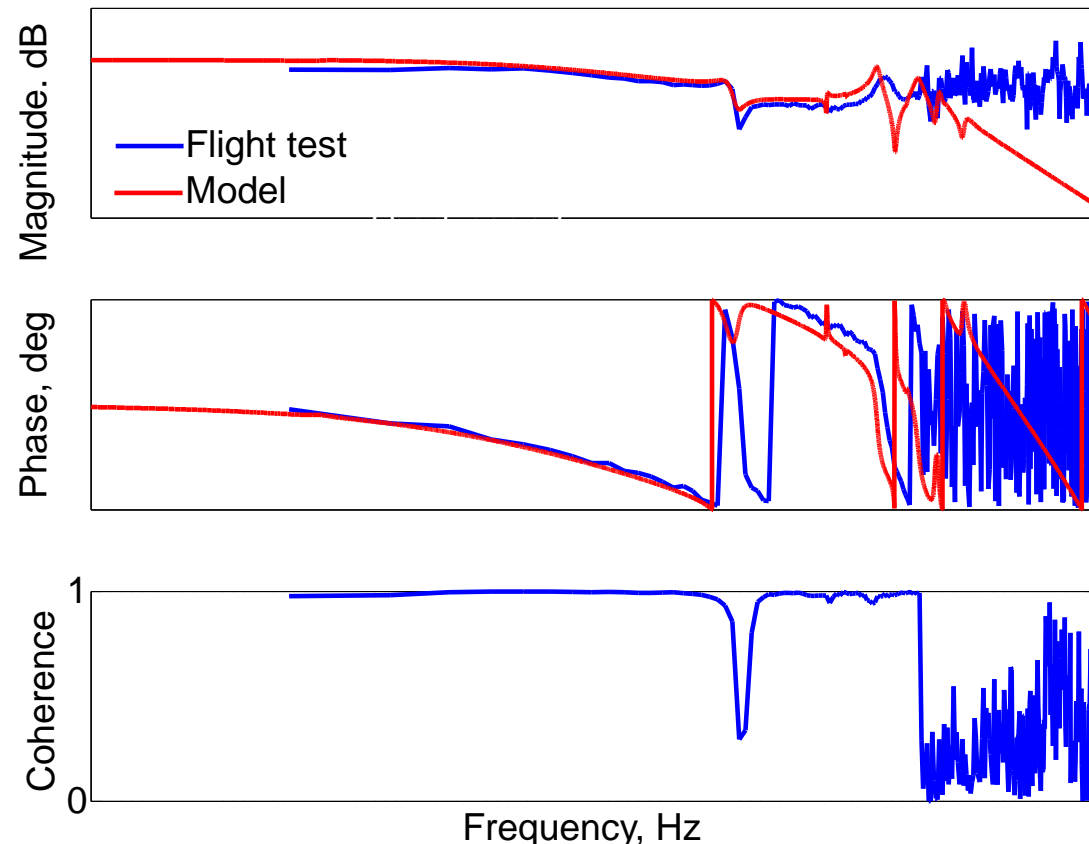
## WING TIP ACCELEROMETER



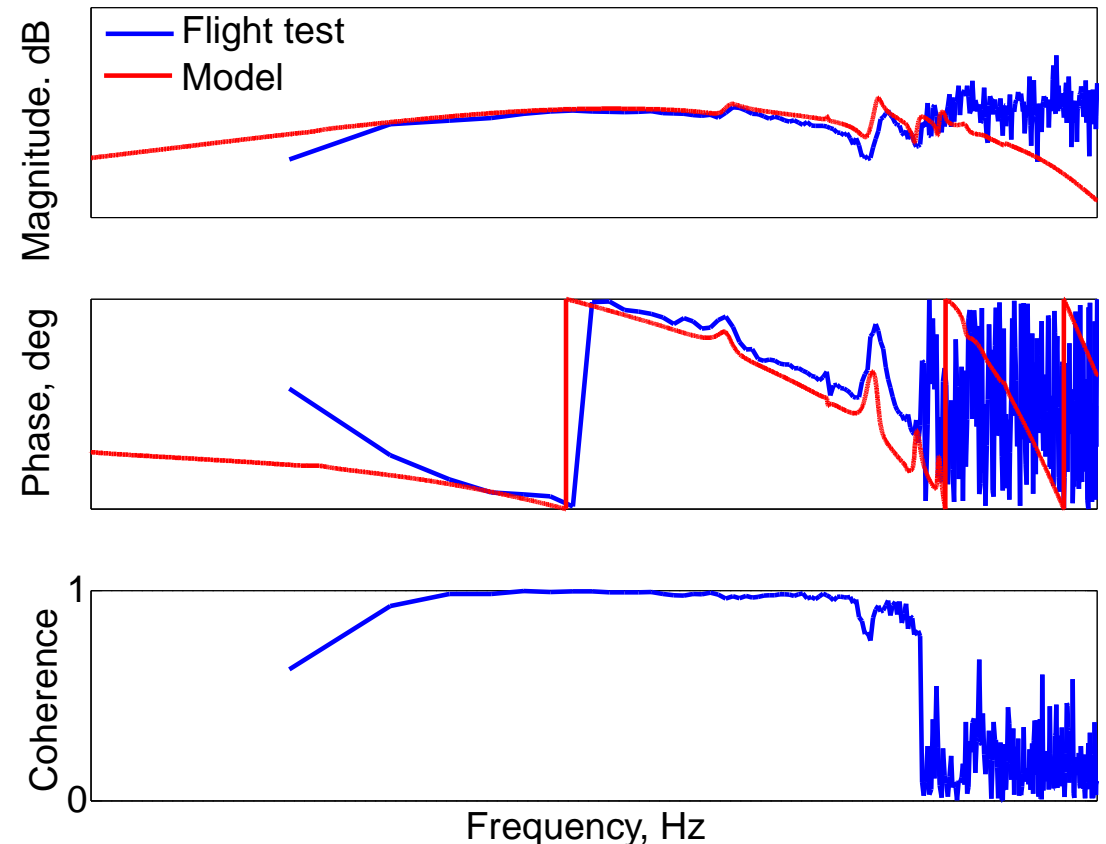
# Flight Data Comparison: Roll Response, low fuel, high speed

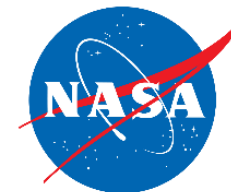


## ROLL RATE



## WING TIP ACCELEROMETER





# Conclusions

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Model generation for body freedom flutter

Addressing issues in:

- State Consistency
- Low frequency dynamics
- Unsteady aerodynamics

Applied approach to X-56A MUTT

- Comparing to flight test data

Details in paper AIAA 2017-0019